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Subjective study of two large music studios

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Summary

Users of two BBC large music studios (Maida Vale 1 and Glasgow 1) were asked to give their opinions on various acoustic characteristics of these studios using a specially devised questionnaire. Three statistical methods of analysing the raw data were used and the results obtained are outlined in this report. One aspect of the work concerns users' views on what would constitute an 'ideal' music studio and these are compared with their assessments of a real studio. Some tentative conclusions are drawn about which individual characteristics are most in need of improvement. The report also attempts to answer the question as to which characteristics determine the overall opinion on a 'like/dislike' axis, and simple equations are deduced which correlate well with the stated opinions of the observers. Factor analysis was used to determine whether a smaller number of variables (derived from the characteristics used for the raw data) could adequately account for the results but little success was achieved using the principal-components method.

Issued under the authority of

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SUBJECTIVE STUDY OF TWO LARGE MUSIC STUDIOS

Section Title Page

Summary .... Title Page

1. Introduction 1

2. The questionnaire 1

3. Analysis 1

3.1. Simple statistical analysis 2
  3.1.1. Real Maida Vale Studio 1 2
  3.1.2. 'Ideal' Studio (Maida Vale observers) 3
  3.1.3. Real Glasgow Studio 1 4
  3.1.4. 'Ideal' Studio (Glasgow observers) 5
  3.1.5. Comparison of the 'Ideal' Studios 5
  3.1.6. Comparison of the real Studios 6
3.2. Correlation analysis 6
  3.2.1. General 6
  3.2.2. Real Maida Vale Studio 6
  3.2.3. 'Ideal' studio (Maida Vale observers) 7
  3.2.4. Real Glasgow Studio 1 8
  3.2.5. Ideal studio (Glasgow observers) 8
3.3. Factor analysis 8
  3.3.1. General 8
  3.3.2. Real Maida Vale Studio 1 9
  3.3.3. Ideal Maida Vale Studio 1 10
  3.3.4. Real Glasgow Studio 1 10

4. Conclusions 11

5. References 11

Appendix 1 12

Appendix 2 15

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SUBJECTIVE STUDY OF TWO LARGE MUSIC STUDIOS

W.N. Sproson, M.A.(Cantab.), F.Inst.P.

1. Introduction

Over a period of some years there has been a mild but growing dissatisfaction with the acoustic quality of the large music studio in Maida Vale (MV1). This dissatisfaction applies particularly when a full symphony orchestra or a large ensemble of players are performing in the studio; when the studio is used for recitals involving only one or two instruments or soloists it is regarded with much more favour, even to the extent of being regarded as completely satisfactory by some people. The dissatisfaction felt when large orchestras are using it, and in particular the BBC Symphony Orchestra which is based there, has been fairly clearly expressed by some individuals although a concensus of opinion is more difficult to define. Some ten or so years ago this particular studio was regarded as a good one by some experts[1] and it would be interesting and instructive (if this were possible) to know why there appears to have been a change of opinion. Be that as it may, there is a feeling of less than complete satisfaction with this orchestral studio and, in view of the possibility of using acoustic modelling[2] to effect improvements, it was considered highly desirable to determine the nature of these complaints.

The aforementioned acoustic modelling work made use of a model of the Maida Vale Studio 1 for two purposes: the first was to establish whether technology had reached the point where modelling was a useful and helpful technique, and whether the quality of sound produced using the model could be considered to be a sufficiently close replica of sound from the real studio. If and when this point had been established, it was then proposed to use the model to determine whether any practicable variations of the acoustic treatment of the studio or lay-out of the orchestra would give rise to better sound quality.

Before starting these experiments, it was felt desirable to ask the various users (sound engineers, musicians, audience) what was wrong with Maida Vale Studio 1. To this purpose a questionnaire was designed and distributed to the appropriate people and this report consists principally of an account of an attempt to analyse the results obtained. The ultimate aim of all work of this kind is to establish significant correlation between subjective opinions about concert halls and objective measurements of relevant acoustical parameters: in this way one hopes eventually to be able to state in objective terms what is responsible for producing good acoustic quality.

Although the original intention of the present work had been restricted to an investigation of Maida Vale Studio 1, it was subsequently found possible to visit Glasgow and to secure the co-operation of the BBC Scottish Symphony Orchestra. Thus the work includes a study of Glasgow Studio 1 and also some interesting comparisons between the two studios.

2. The questionnaire

A draft questionnaire was first distributed to some senior sound engineers intimately concerned with sound recording in Maida Vale, and in view of their favourable comments the main experiment used the questionnaire in a virtually unmodified condition (See Appendix 1). Nineteen individual characteristics were included in addition to a general overall response on a 'Like/Dislike' axis. It is not considered that as many as nineteen characteristics are required to specify sound quality, but at this stage in the investigation it was felt desirable to include all the terms which might usefully help to convey a full picture. Hopefully the total number of completely independent variables would not exceed four or five, but there was no guarantee that a set of truly independent variables (orthogonal in multi-dimensional space) would correspond precisely to any of the terms normally used to describe acoustic quality, e.g. the terms used in this questionnaire. It will be noted that in fact all the terms do relate directly to acoustic quality and that other matters which might have had a bearing on the subject, but far less directly, were not included, e.g. conditions of lighting (this affects the musicians with respect to ease of reading their scores), air conditioning, décor, etc.

In compiling the list of terms to be used, attention was paid to the lists used by other workers for similar purposes, e.g. Beranek,[3] R. Hawkes (University College London),[4] and hopefully the terms selected include, explicitly or implicitly, all those previously used.

3. Analysis

The number of completed questionnaires relating to the acoustics of the Maida Vale studio was disappointingly small, and in fact numbered only twenty-five. The 'catchment area' did not include as wide a range of personnel as had been hoped, and mainly embraced engineering staff engaged in sound broadcasting. Due to various difficulties is was not possible to obtain replies from all members of the BBC Symphony Orchestra, but the Orchestral Committee agreed to take part. In addition to inquiring about the observers' reactions to the real Maida Vale studio, fourteen engineers and musicians also filled in questionnaires giving their views on the rating of an ideal music studio, and some of the analysis which follows will refer to these questionnaires.

In purely numerical terms, greater success was achieved with the study of Glasgow Studio 1, where fifty-six completed questionnaires were obtained relating to the real Glasgow studio and another fifty-six relating to the musicians' opinions about an ideal music studio. In due course certain interesting similarities will be pointed out between the assessments in London and Glasgow.

Three methods of analysis will be reported upon;

1. Simple statistical analysis making use of means and standard deviations. This will include comparison of the real with the ideal studio.
2. Correlation analysis which, inter alia, attempts to establish a simple mathematical relationship between the overall assessment and those individual characteristics which contribute significantly to the overall assessment;
3. Factor analysis. This is a more sophisticated version of correlation analysis and gives as its end product the relationship between the overall assessment and combinations of the individual variables which are, in the mathematical sense, orthogonal. These combinations of the individual variables are termed factors.

3.1. Simple statistical analysis

3.1.1. Real Maida Vale Studio 1

The prefix 'real' is used here to distinguish the studio from the 'ideal' studio which will be reported on in Section 3.1.2, or the 'model' studio used in the acoustic scaling experiment.

The means and standard deviations for the twenty qualities reported upon by the twenty-five observers are given in Table 1 (for compactness and ease of comparison Table 1 also gives data on the 'ideal' studio). The polarity of the numbering is given in Appendix 1 and usually proceeds from the 'undesirable' condition, rated at 0, to the 'desirable', rated at 10. This simple system does not obviously apply to some qualities, since either extreme may be undesirable and in that case Appendix 1 must be consulted. For example, the polarity is obvious for characteristic No. 20 'overall', where 0 = disliked, 10 = liked, or characteristic No. 13 'definition', where 0 = muddy, 10 = clear. A more difficult case, however, is characteristic No. 10 'intimacy', where it has been decided to label 'distant' as 0 and 'intimate' at 10, although one may not wish for either extreme in practice.

Examination of Table 1 shows that certain characteristics secure high numerical gradings. Thus 'echoes' (No. 3) are graded at 8·34 ± 1·27, 'pitch changes' (No. 4) at 8·01 ± 2·03 and 'loudness' (No. 9) at 6·47 ± 1·72.

The first two of these three characteristics certainly imply a favourable grade in the sense that the studio is substantially free from echoes and from pitch changes; for the third (loudness) this is not necessarily so because a studio can sound too loud, and this may well be the case for Maida Vale 1 (see Section 3.2.2, for correlation analysis tending to substantiate this).

Turning now to the characteristics securing the lowest gradings, 'intimacy' (No. 10) is rated at 3·80 ± 2·42, 'hardness' (No. 8) at 3·88 ± 2·17, 'timbre' (No. 19) at 4·08 ± 2·14 and 'overall' (No. 20) at 4·10 ± 2·39. It does not automatically follow that a low numerical grading proves that the studio is deficient in a praticular quality and characteristic; No. 10 'intimacy' has already been discussed in order to illustrate this point. Discussion of this is usefully deferred until the characteristics of the 'ideal' studio have been considered (Section 3.1.2). Nevertheless, little doubt attaches to the significance of low ratings of characteristics 19 and 20 and it would appear that the studio is to some extent lacking in timbre and is below the half-way mark on the 'dislike' to 'like' axis used for assessing the 'overall' response. Of course, it may be argued that if a criticism of a studio is sought, it is almost certain that one will be forthcoming, and therefore the fact that the overall grading is less than 5 should not be taken as too significant. In fact, the distribution of opinions on 'overall' show a bimodal distribution: 15 observers gave ratings below 4, and 10 gave ratings above 5·7 with a gap in the middle range from 4 to 5·7. This suggests two schools of thought about Maida Vale 1, those who view it favourably, and those with a moderate to strong dislike (two observers graded the studio at 0!).

TABLE 1
Summary of Assessments of Observers on Maida Vale 1 Studio

Quality	Real Studio		'Ideal' Studio	
	mean	standard deviation	mean	standard deviation
1. Colouration	4·96	2·45	7·65	2·78
2. Diffusion	5·90	2·64	8·00	2·21
3. Echoes	8·34	1·27	7·92	2·62
4. Pitch Changes	8·01	2·03	9·03	1·05
5. Singing Tone	4·87	2·54	9·62	1·41
6. Ensemble	4·23	2·67	9·19	0·68
7. Fullness of Tone	5·17	2·49	8·94	1·39
8. Hardness	3·88	2·17	6·44	2·40
9. Loudness	6·47	1·72	5·77	1·62
10. Intimacy	3·80	2·42	5·73	1·97
11. Liveness	5·06	2·55	7·57	1·68
12. Tonal Warmth	4·56	2·42	8·73	2·00
13. Definition	4·77	2·78	8·19	1·36
14. Brilliance	5·10	2·37	7·23	1·70
15. Balance	4·26	2·52	9·33	0·68
16. Blend	5·17	2·68	9·06	1·74
17. Attack	6·00	2·00	8·98	1·39
18. Dynamic Range	5·06	2·54	8·88	1·62
19. Timbre	4·08	2·14	9·50	0·92
20. Overall	4·10	2·39	9·79	0·38

Numerical data of the kind listed in Table 1 is not easy to interpret and Figure 1 is offered as a 'profile' of the studio. No particular meaning attaches to the shape given in Figure 1, but it is useful in comparing other studios when plotted in the same way; similarities and differences then become immediately apparent. Figure 1 looks rather like the shape that might be expected if the peaks of random noise pulses were joined by straight lines, except for the peaks at characteristics Nos. 3 and 4 which have already

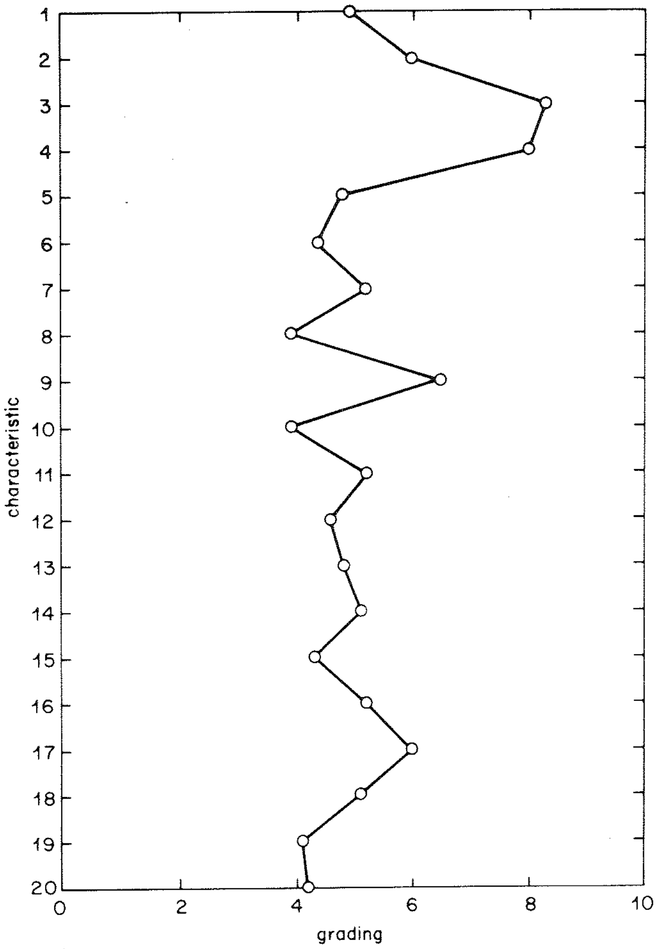

Fig. 1 - Profile of real Maida Vale 1 Studio

been commented on. Most of the mean gradings lie in the range 4 to 6 and the mean of all the mean gradings is 5·19.

3.1.2. 'Ideal' Studio (Maida Vale observers)

Fourteen of the twenty-five observers who filled in questionnaires on the real Maida Vale studio gave their opinions on what would (within these terms of reference) constitute an ideal studio. The mean gradings and standard deviations are given in Table 1 and a profile is shown in Figure 2. One immediate observation on Figure 2 is that some 'Ideal' characteristics are well removed from a rating of 10 and these are 'hardness' (No. 8), 'loudness' (No. 9) and 'intimacy' (No. 10) where a rating of about 6 is chosen. Although values close to 10 might be expected for most of the characteristics, in fact the average rating is only about 8, and only in the case of characteristics Nos. 5, 6, 15, 19 and 20 are the mean ratings above 9. It will also be noted that the profiles shown in Figures 1 and 2 are different in both shape and level. The 'ideal' rating for 'loudness' is 5·77 as against 6·47 for the 'real' studio, and this supports the view expressed that Maida Vale Studio 1 is too loud (although not by too large an amount if the numerical difference in grading has quantitative significance).

Some of the answers are a little surprising and imply that there may be a linguistic or semantic difficulty. In the view of acousticians, a good studio should be free from colourations and thus characteristic No. 1 should be rated 10. In fact it was rated at 7·65 with a relatively large standard deviation (2·8). It is possible that, for some observers, absence of colouration is wrongly thought to mean a colourless studio in the sense of lifeless or dead. Colouration was one of the few terms defined in the questionnaire (Appendix 1) but this may not have been read or understood by every observer.

A similar difficulty arises with characteristic No. 3 (echoes), and here the confusion may be between discrete echoes, which are usually considered harmful, and reverberation which, in the right amount, is a very desirable characteristic. Echoes were rated at 7·9 (standard deviation 2·6).

In spite of these misgivings, the difference between the profiles shown in Figure 1 and Figure 2 is thought to be significant and indicative of those characteristics which should be changed. Figure 3 plots the differences together with 5% and 1% levels at which the differences are significant (as derived from the standard deviations taken as a whole, not for each individual characteristic). Taking the points outside the 1% level (which means the probability of the two means belonging to the same statistical population is less than 1 in 100) the following changes to MV1 would appear to be desirable, and are listed in Table 2.

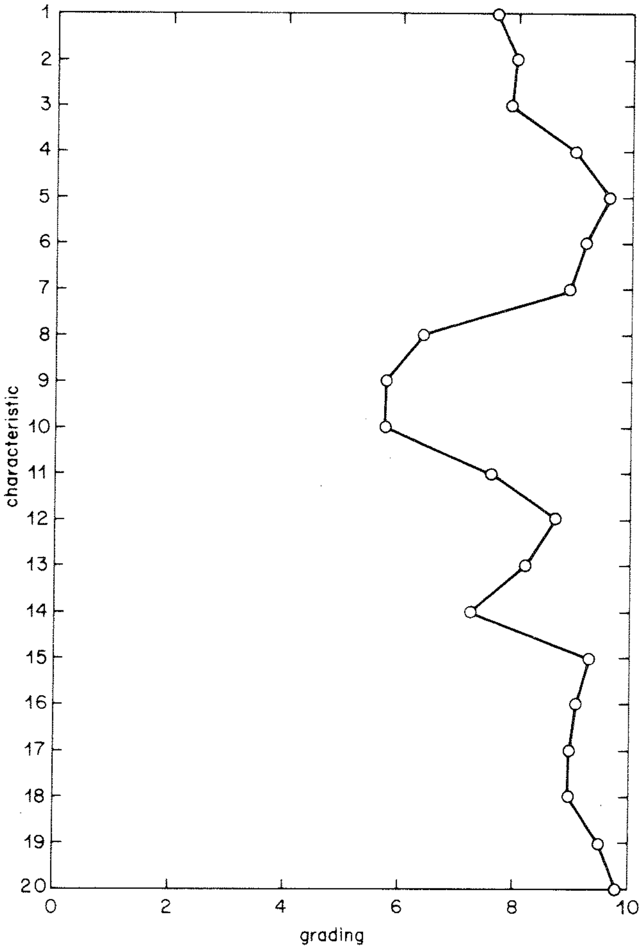

Fig. 2 - Profile of ideal studio (Maida Vale observers)

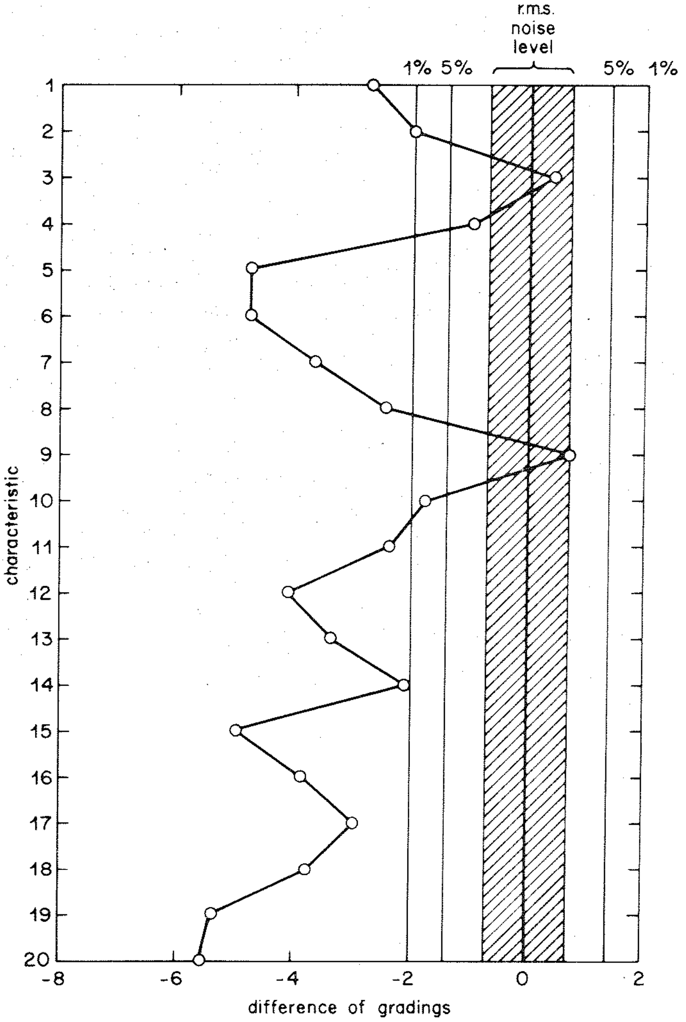

Fig. 3 - Real studio compared with the ideal (Maida Vale observers)

TABLE 2

Characteristic	Description	Direction of change
1	Colouration	Less coloured
5	Singing tone	More singing tone
6	Ensemble	Better ensemble
7	Fullness of tone	More fullness of tone
8	Hardness	More mellow
11	Liveness	More live
12	Tonal warmth	More warmth
13	Definition	More clarity
15	Balance	Better balance
16	Blend	Better blend
17	Attack	Better attack
18	Dynamic range	More dynamic range
19	Timbre	Better timbre

This seems a formidable list and it does not follow that all these changes are possible simultaneously. For instance, Nos. 8 and 13 may be incompatible in the sense that a more mellow studio is unlikely to have better definition (or for that matter, better attack (17)).

It is to be noted that loudness (9) does not appear in the list because the difference in grading is not sufficiently large.

3.1.3. Real Glasgow Studio 1

As stated in the introduction, the original intention of this investigation was to restrict attention to the Maida Vale No. 1 studio, but it was found possible to carry out a similar investigation on the studio which houses the Scottish Symphony Orchestra, namely Glasgow Studio 1, and this section reports the results obtained. Fifty-six observers took part and in contradistinction to the London results, these were obtained exclusively from musicians. The results are given in Table 3 (both for the real studio and the 'ideal' studio). The 'profile' for this studio is given in Figure 4. Most of the mean gradings lie in the range 4 to 6 as was the case with Maida Vale Studio 1; only two characteristics lie outside this range, namely No. 9 (loudness) rated at 7·4, and No. 15 (balance) rated at 2·6. The overall assessment is 4·5 ± 2·5 and like Maida Vale 1 is just below the 'half-way' mark i.e. 5. Whether the comparatively luke-warm comments on this studio imply some measure of dissatisfaction is uncertain, although there have been comments by the conductor and members of the orchestra which imply some criticism. However, as commented for the London studio, it may well be that if one asks for criticism, one is almost certain to receive it.

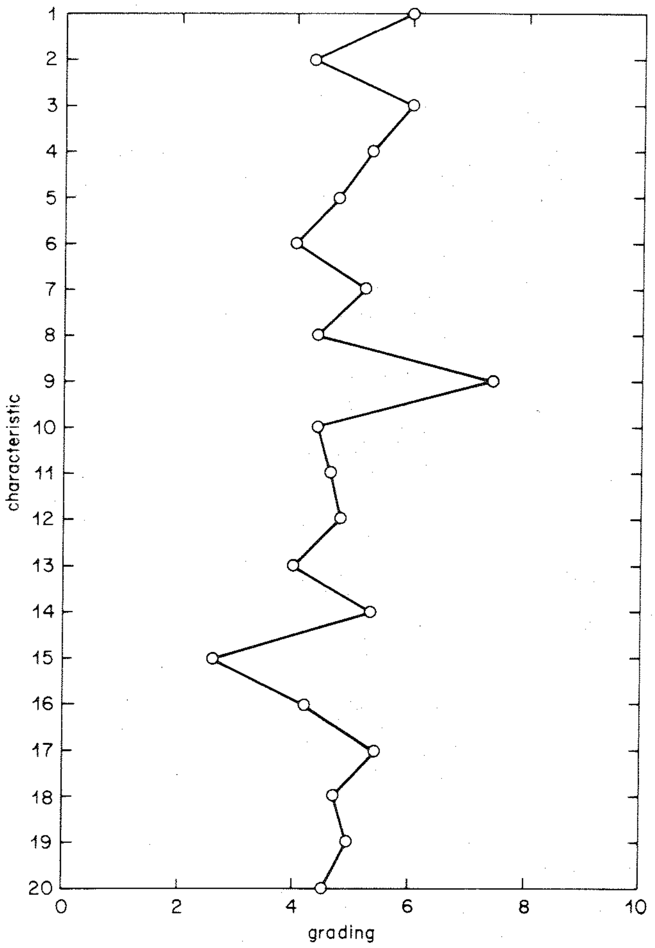

Fig. 4 - Profile of real Glasgow Stduio 1

TABLE 3

Summary of Assessments of Observers on Glasgow Studio 1

Characteristic	Real Studio		Ideal Studio	
	mean	standard deviation	mean	standard deviation
1. Colouration	6·0	2·4	4·8	2·7
2. Diffusion	4·3	2·3	7·7	1·9
3. Echoes	6·0	2·8	6·4	2·0
4. Pitch Changes	5·3	2·7	8·4	2·4
5. Singing Tone	4·7	2·7	8·6	2·0
6. Ensemble	4·0	2·9	9·0	1·4
7. Fullness of Tone	5·2	2·7	8·2	1·7
8. Hardness	4·4	2·4	6·7	1·8
9. Loudness	7·4	2·2	5·7	1·9
10. Intimacy	4·4	2·6	7·0	2·6
11. Liveness	4·6	2·8	8·2	2·0
12. Tonal Warmth	4·8	2·4	7·6	2·4
13. Definition	4·0	2·9	8·8	1·3
14. Brilliance	5·3	2·5	8·0	1·5
15. Balance	2·6	2·1	8·9	2·2
16. Blend	4·2	2·5	8·6	1·6
17. Attack	5·4	2·7	8·9	1·4
18. Dynamic Range	4·7	2·6	8·9	1·4
19. Timbre	4·9	2·3	8·9	1·4
20. Overall	4·5	2·5	9·7	0·6

3.1.4. 'Ideal' Studio (Glasgow observers)

The ratings of the fifty-six musicians of the Scottish Symphony Orchestra on what, in their opinion, constitutes an 'ideal' studio are also given in Table 3 and in Figure 5. Once again it will be noted that the 'ideal' studio is not defined by a set of characteristics all of very high grading, i.e. between 9 and 10. Some characteristics are graded around the half-way mark, and in particular Colouration (No. 1), Echoes (No. 3) and Loudness (No. 9), are graded at 4·8, 6·4 and 5·7 respectively. The linguistic difficulty again appears to apply to characteristic No. 1 (Colouration) in that the mean opinion for an 'ideal' studio suggests a grading of approximately 5, whereas Colouration, in the acoustician's definition of the term, is something that should be absent and, when absent, produce a grading of 10 or near to 10. The grading of Echoes at 6·4 is likewise not fully understood and maybe the same comment applies as with Maida Vale (Section 3.1.2). The two characteristics which rate between 9 and 10 are No. 6 (Ensemble) at 9·0, and No. 20 (Overall) at 9·7.

The differences between the real and 'ideal' ratings are plotted in Figure 6, and as with Maida Vale Studio 1, a large number of characteristics give significant differences at the 1% confidence level; in fact this particular studio would appear to be marginally satisfactory in respect of only two characteristics, namely Colouration (No. 1) and Echoes (No. 3): it is significantly too loud (characteristic No. 9) and in respect of all the other characteristics it is apparently deficient. This adverse judgement is possibly a little extreme, but nevertheless it is what emerges from the analysis.

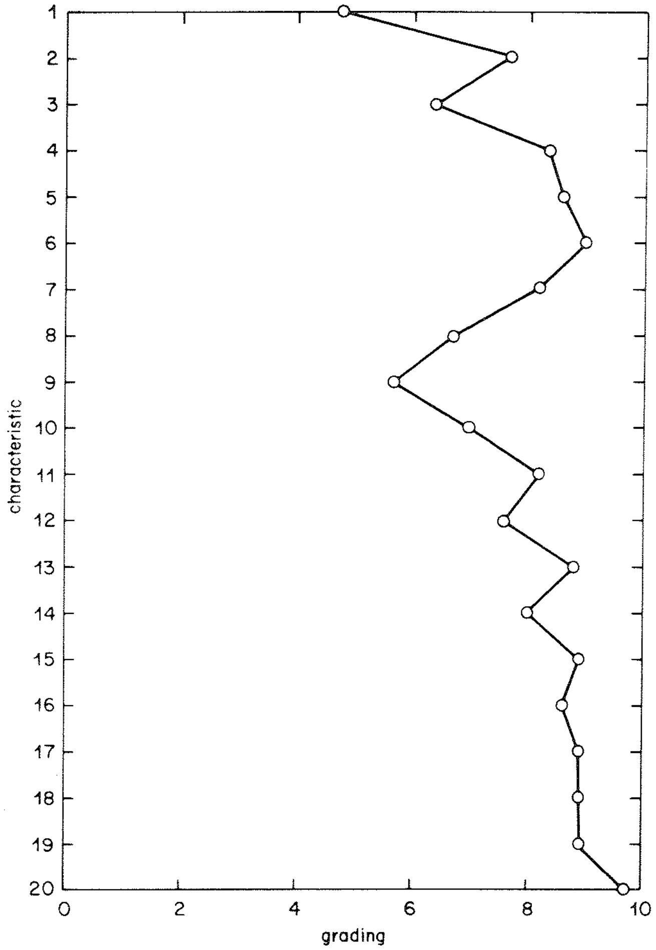

Fig. 5 - Profile of ideal studio (Glasgow 1 observers)

3.1.5. Comparison of the 'Ideal' Studios

Sections 3.1.2 and 3.1.4 report on the views of two very different groups of observers as to what constitutes an 'ideal' studio. If the results are compared, i.e. Tables 1 and 2 or Figures 2 and 5, it will be observed that there is a significant degree of agreement on almost all the characteristics. The two about which there is some disagreement are Colouration and Echoes, and it has been pointed out that some, if not the majority, of observers appear to have difficulty in understanding these two characteristics, in the sense in which they are defined by acousticians. Not only are the backgrounds of the two groups of observers different, but also the studio which they are most accustomed to use. Thus Maida Vale 1 is relatively squat and has a height to width ratio of 0·44 at the centre falling to 0·28 at the sides, whereas Glasgow Studio 1 is much taller and has a height to width ratio of 0·74. The volumes of the studios are roughly similar; Maida Vale = 6,250 cubic metres, and Glasgow = 5,150 cubic metres.

Although the 'ideal' studios envisaged by the two groups of observers appear to have strong similarities, it is difficult to be sure whether or not this is pure coincidence. Statistical tests suggest that it is highly significant.

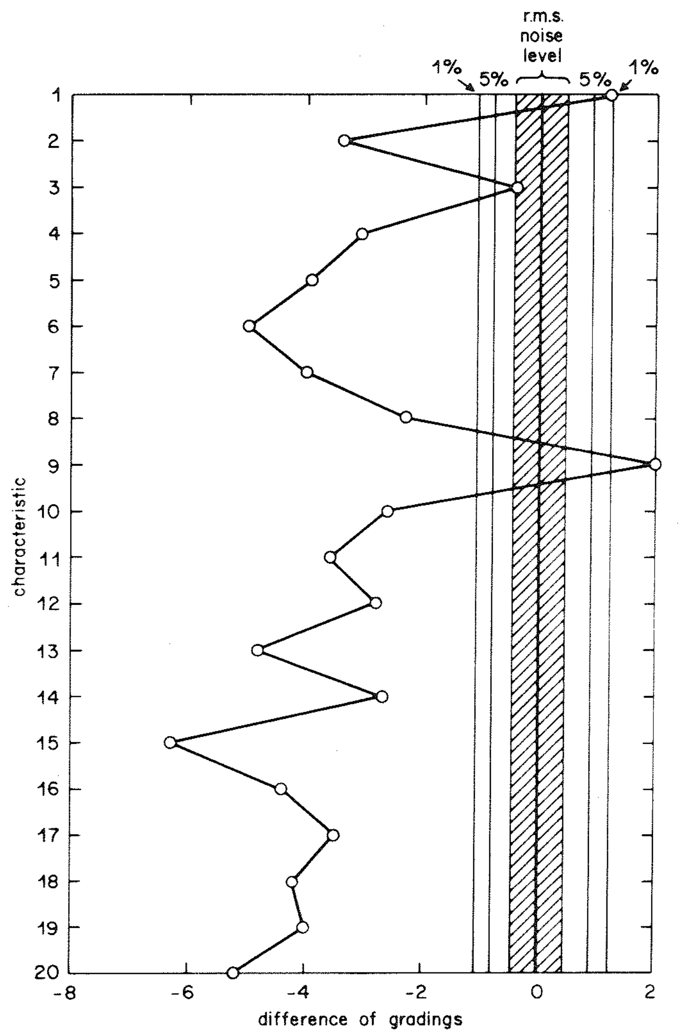

Fig. 6 - Real studio compared with the ideal (Glasgow observers)

3.1.6. Comparison of the real Studios

The similarity between the 'ideal' studio just discussed would also appear to apply to a comparison of the real studios, although not quite to the same extent. If Figures 1 and 4 are superposed, both graphs show a peak at characteristic No. 9 (i.e. both studios sound too loud); the general trend of ratings between the gradings of 4 to 6 appears to be roughly similar and the only points of possibly significant difference are characteristics Nos. 3 and 4 (Echoes and Pitch Changes), where Maida Vale 1 scores high ratings, and characteristic No. 15 (Balance) where Glasgow has a lower rating. It may or may not be relevant that both studios are the subjects of criticism at the present time.*

3.2. Correlation analysis

3.2.1. General

Correlation analysis is a powerful mathematical tool whereby it is possible to determine from a mass of data whether certain characteristics are closely (or not so closely) related to others and to determine, say, by linear regression whether a simple linear equation can serve as an adequate statistical substitute for the data. It is not usually possible to claim that the equation explains the phenomena involved because correlation analysis does not deal with cause and effect. In the present study, it may be possible to determine a linear equation which predicts with reasonable accuracy the overall assessment from a selected list of individual characteristics; in such circumstances a mathematical model has been devised which more or less accounts for the data and which may give some insight into how different characteristics are (subconsciously or otherwise) weighted to give the overall results.

Correlation deals with variations from mean values. It therefore has nothing to say about the importance or significance of quantities that, in a given experiment, are invariant or nearly so. To take an example, 'Echoes' (characteristic No. 3) are consistently rated highly in the real Maida Vale Studio 1 and this means that the studio is agreed to be substantially free from echoes. Therefore it is unlikely that correlation analysis will include 'echoes' as a relevant characteristic. It would be quite erroneous, however, to assume that freedom from discrete echoes is unimportant. The analysis about to be discussed concerns characteristics about which there is a variation of opinion and how this variation affects individual judgements of overall assessment.

3.2.2. Real Maida Vale Studio

The symmetrical matrix of 20 x 20 correlation coefficients relating to observations on the real studio was evaluated by computer. An examination of this matrix indicated that eight independent variables were significantly related (at the 1% level or lower) to the overall assessment and, on this basis, linear regression for nine variables was carried out resulting in Equation (1).

$$\begin{aligned} R_{20} = &- 0{\cdot}002R_5 + 0{\cdot}201R_6 - 0{\cdot}387R_9 - 0{\cdot}114R_{13} \\ &+ 0{\cdot}136R_{15} + 0{\cdot}204R_{16} + 0{\cdot}148R_{18} \\ &+ 0{\cdot}361R_{19} + 2{\cdot}455 \qquad (1) \end{aligned}$$

where R_{20} = rating of characteristic 20 (overall)
R_5 = rating of characteristic 5 (singing tone)
R_6 = rating of characteristic 6 (emsemble)
R_9 = rating of characteristic 9 (loudness)
R_{13} = rating of characteristic 13 (definition)
R_{15} = rating of characteristic 15 (balance)
R_{16} = rating of characteristic 16 (blend)
R_{18} = rating of characteristic 18 (dynamic range)
R_{19} = rating of characteristic 19 (timbre)

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* Maida Vale 1 has just had its orchestral layout modified in an attempt, inter alia, to improve the acoustics, and Glasgow 1 is being refurbished for stereophonic operation.

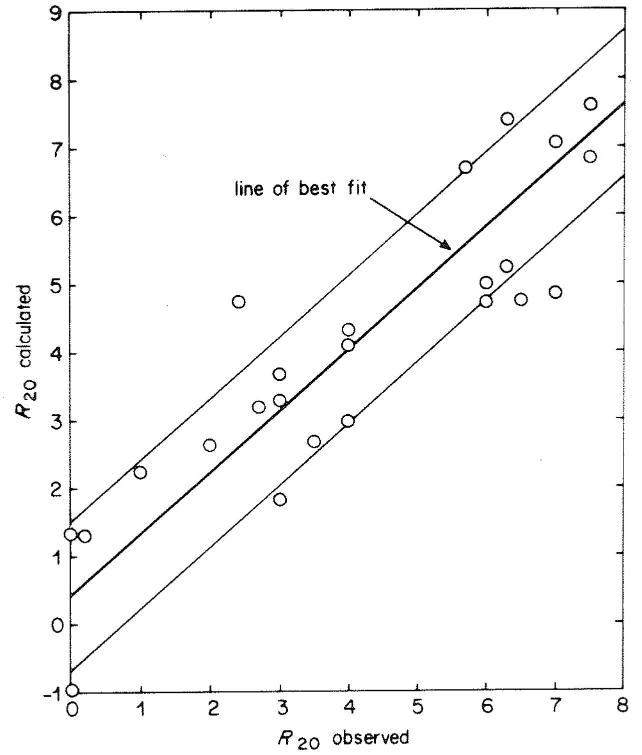

Fig. 7 - Linear regression applied to the real Maida Vale Studio 1

The multiple correlation coefficient was 0·893, which is a measure of the success of this particular mathematical approach. Figure 7 shows the overall assessment derived from Equation (1) versus that directly stated by each of the 25 observers. Clearly there is a trend in the results shown in Figure 7, but in terms of accuracy of estimation, Figure 7 reveals errors of up to 2·4. The standard error of estimate is given by the formula.

$$\text{S.E.} = \sigma(1 - r^2)^{\frac{1}{2}} \qquad (2)$$

where S.E. = standard error of estimate
σ = standard deviation (of R_{20})
r = multiple correlation coefficient.

In the present case σ = 2·09, r = 0·893 whence S.E. = 0·94.

Thus the standard error of estimate has a value of approximately one unit, or one tenth of the total scale used in this study. The weightings of the individual characteristics reveal some interesting features:

(a) The weighting of R_9 (loudness) is negative, implying that an increase produces, on the average, a lower value of R_{20} (overall).

(b) The weighting of R_5 (singing tone) is very small, implying that it has little effect on the overall assessment R_{20} (overall).

(c) The largest positive weighting coefficient, 0·361, applies to R_{19} (timbre) which thus appears to exert most influence on the overall assessment R_{20}.

(d) The weighting of R_{13} (definition) is negative which would appear to imply that the 'definition' of Maida Vale Studio 1 is too clear on a scale which goes from 'muddy' to 'clear', and possibly agrees with a comment that the studio is too 'hard'.

(e) The weighting of R_{16} 'blend' has the second largest positive coefficient and this possibly supports the negative weighting of R_{13}, 'definition'; against this, however, R_2, 'diffusion', does not appear in the correlation analysis.

Figure 3 and Table 2 (Section 3.1.2) showed the extent to which the 'real' studio fell short of the 'ideal'. It is pertinent to enquire whether correlation analysis shows the same characteristics. Table 4 shows (in order of importance*) the first seven characteristics.

TABLE 4

First Seven Characteristics Requiring Attention

Order	Difference of mean gradings (Fig. 3)	Weighting coefficient (Eq. 1)
1	Timbre (No. 19)	Loudness (No. 9) (Negative)
2	Balance (No. 15)	Timbre (No. 19)
3	Singing tone (No. 5)	Blend (No. 16)
4	Ensemble (No. 6)	Ensemble (No. 6)
5	Tonal warmth (No. 12)	Dynamic Range (No. 18)
6	Blend (No. 16)	Balance (No. 15)
7	Dynamic Range (No. 18)	Definition (No. 13) (Negative)

One immediate difficulty in lining up the two sets shown in Table 4 is the negative weighting coefficients for 'loudness' and 'definition'. Loudness (No. 9) is on the opposite side of the zero line in Figure 3 to almost all the other characteristics, although not to a significant extent. With 'definition' (No. 13) there is a complete contradiction because Figure 3 and Table 2 imply that more clarity is required: Equation (1) says that there is too much clarity. All the remaining five characteristics, however, are in both lists, namely timbre, balance, ensemble, blend and dynamic range. Thus it can be said that agreement exists on five characteristics when two different approaches to the observers' data are used.

3.2.3. 'Ideal' studio (Maida Vale observers)

It is not possible to perform correlation analysis with reference to 20 variables when only 14 completed questionnaires are available. Further, since the overall assessments are in the restricted range 9 to 10, any form of correlation analysis is not likely to yield very useful results (because the dependent variable is nearly constant). Regression analysis, using the variables found to be significant in the study of the real studio, was carried out, however, and the resulting 'best fit' equation is as follows:

---

* It is here assumed that importance is directly related to either weighting coefficient or difference of mean gradings (see Appendix 3).

$$R_{20} = 0{\cdot}084R_5 + 0{\cdot}664R_6 + 0{\cdot}066R_9 + 0{\cdot}086R_{13} + 0{\cdot}346R_{15} - 0{\cdot}063R_{16} + 0{\cdot}027R_{18} - 0{\cdot}399R_{19} + 2{\cdot}262 \qquad (3)$$

using the same symbols as in Equation (1).

This equation has the surprisingly high multiple correlation coefficient of 0·955: the restricted range of R_{20} makes it doubtful how much significance in the psycho-acoustic sense should be inferred, although statistical significance is apparently very high.

The characteristics which appear to have most control over the final assessment are, in order of weighting coefficient:

ensemble (No. 9)
timbre (No. 19)
balance (No. 15)

(other characteristics have a weighting coefficient of less than 0·10)

The negative coefficient for 'timbre' is not understood, since good timbre is an undisputed requirement of a studio and it is not one of the characteristics where an extreme is obviously undesirable. Perhaps this result should be taken as a warning about the limitations of input data of restricted range whatever the statistical tests of significance may imply. In view of this, it was not considered profitable to analyse the consequences of Equation 3 in greater detail.

3.2.4. Real Glasgow Studio 1

Linear regression analysis applied to the 56 questionnaires relating to the real Glasgow Studio 1 was carried out with reference to the nine independent variables which were significantly correlated (at the 5% or lower level*) with overall assessment. Equation (4) gives the resulting linear formula.

$$R_{20} = 0{\cdot}203R_5 + 0{\cdot}095R_6 + 0{\cdot}206R_{10} - 0{\cdot}047R_{12} + 0{\cdot}091R_{14} + 0{\cdot}380R_{15} + 0{\cdot}253R_{16} + 0{\cdot}106R_{17} - 0{\cdot}620 \qquad (4)$$

The ninth variable R_{19} has been omitted because the coefficient (−0·0003) was so small a value as to have no perceptible influence on the result.

The multiple correlation coefficient is 0·747 which is highly significant (the change of this occurring by random probability is much less than 0·1%), but the standard error of estimate is (as Equation (2))

$$\text{S.E.} = \sigma(1 - r^2)^{\frac{1}{2}} = {\cdot}4415 \qquad \sigma = 1{\cdot}10$$

The negative sign describing R_{12} (tonal warmth) is not understood, but at least the magnitude of the coefficient is small compared to the other coefficients.

It is instructive to compare (as in Section 3.2.2) those characteristics which were shown to be most deficient when the mean gradings of the ideal studio were subtracted from those of the real studio (Figure 6) with the characteristics in Equation (4) taken in order of weighting coefficient. Table 5 collates the data.

TABLE 5

The First Eight Characteristics Requiring Attention

Order	Difference in mean grading (Fig. 6)	Weighting coefficient (Eq. 4)
1	Balance (No. 15)	Balance (No. 15)
2	Ensemble (No. 6)	Blend (No. 16)
3	Definition (No. 13)	Intimacy (No. 10)
4	Blend (No. 16)	Singing Tone (No. 5)
5	Dynamic Range (No. 18)	Attack (No. 17)
6	Fullness of Tone (No. 7)	Ensemble (No. 6)
7.	Timbre (No. 19)	Brilliance (No. 14)
8	Singing Tone (No. 5)	Tonal Warmth (No. 12) (Negative)

In the case of Maida Vale Studio 1, five of the seven characteristics listed in Table 4 were common to both lists: here the agreement is rather less in that only four of the eight characteristics are common, namely balance, blend, ensemble and singing tone. Balance is the most important characteristic in both lists; the others vary in their respective placings. Since two dissimilar methods give these four characteristics it would seem highly probable that suitable improvements relating to balance, blend, ensemble and singing tone would produce an appreciably better studio, at least in the view of the members of the BBC Scottish Symphony Orchestra.

3.2.5. Ideal studio (Glasgow observers)

Correlation/regression analysis was not applied to the individual ratings of the ideal studio because it is not thought to be a likely source of useful information and the anomalous results reported in Section 3.2.3 tended to support this view.

3.3. Factor analysis

3.3.1. General

Several approaches to factor analysis are described in the literature.[5] The one which has been used in the present work is the 'principal components' method, which is capable of producing 'm' orthogonal factors from 'n' original variables contained in N sets of data ($m \leqslant n < N$); the factors are selected in decreasing order of their variances. One undesirable feature of this method is that each factor uses all the original 'n' variables, although, hopefully, certain of the variables might dominate and others be of much less importance. Whether the 'm' orthogonal factors correspond to qualities which have any physical or psycho-physical significance is something that cannot be predicted. The mathematical proceedure amounts to finding the latent roots in an m x n matrix equation: orthogonality and decreasing order of variances can be guaranteed but are not necessarily of physical or psycho-physical significance.

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* In the corresponding analysis for Maida Vale 1, the 1% level was chosen because a higher general level of correlation held in that studio and eight variables 'qualified'. At the 1% level, five variables 'qualified' for Glasgow 1 and it was decided to include four additional variables in the 5% to 1% category. The analysis effectively eliminates variables which are not important in terms of the final 'best-fit' equation.

The purpose of factor analysis is to reduce the number of variables required to describe a situation to the minimum compatible with no significant loss of information. Nineteen independent variables have been used in the questionnaire, but as stated in Section 2, it is thought unlikely that nineteen variables (when optimally defined) will be required to describe the acoustic quality of a studio. In more recent studies, the number of factors has been arbitrally set to seven in the hope that seven or less factors (i.e. qualities or combinations of qualities) should be sufficient.

3.3.2. Real Maida Vale Studio 1

Factor analysis was applied to the 19 independent variables contained in the 25 questionnaires and the first seven factors were extracted by the Elliott 803 computer using a factor analysis programme. The first seven factors extracted 83·5% of the total variance. A detailed and careful examination of these factors failed to reveal any physical significance attached to the individual factors: one disappointing feature was the absence of any clear differentiation between qualities which dominated and those which were much smaller in importance. For example, the first factor (F1) (standard deviation, σ = 5·7098) included fifteen of the nineteen variables with gradually decreasing weighting coefficients (starting with No. 5 (singing tone) coefficient = 0·8279 and finishing with No. 10 (intimacy) coefficient = 0·2082) before there was any appreciable change in ratios of successive coefficients. This factor (F1) correlates well with the overall assessment No. 20 (correlation coefficient, r = 0·809), but a factor which includes almost all the variables is not capable of any easy interpretation. The second factor, F2, included seventeen variables before any 'break-point'. The only factors where there was a clear tendency for a single (or just a few) variables to separate out were F4 and F5, where echoes and intimacy, respectively, were outstanding from the remaining variables by ratios of nearly two to one. Neither of these factors, however, correlates significantly with the overall assessment. The complete results are given in Appendix 2.

During the course of the work, it became apparent that the original data from a rather limited number of questionnaires (N = 25) did not much exceed the number of independent variables (n = 19), and therefore some degree of correlation may well have existed even if the original data has been sets of random numbers. Indeed, this thought prompted a run of the programme with two sets of data consisting entirely of random numbers. The variances extracted by the first seven factors were 72% and 70% respectively, which is well above the 37% (7/19ths) which would be expected from random numbers if N greatly exceeded n. In other words, short sequences of random numbers are bound to show correlations and the notion of a short sequence of random numbers is untenable. The conclusion from this part of the study was that the number of questionnaires was very inadequate for this kind of powerful mathematical analysis.

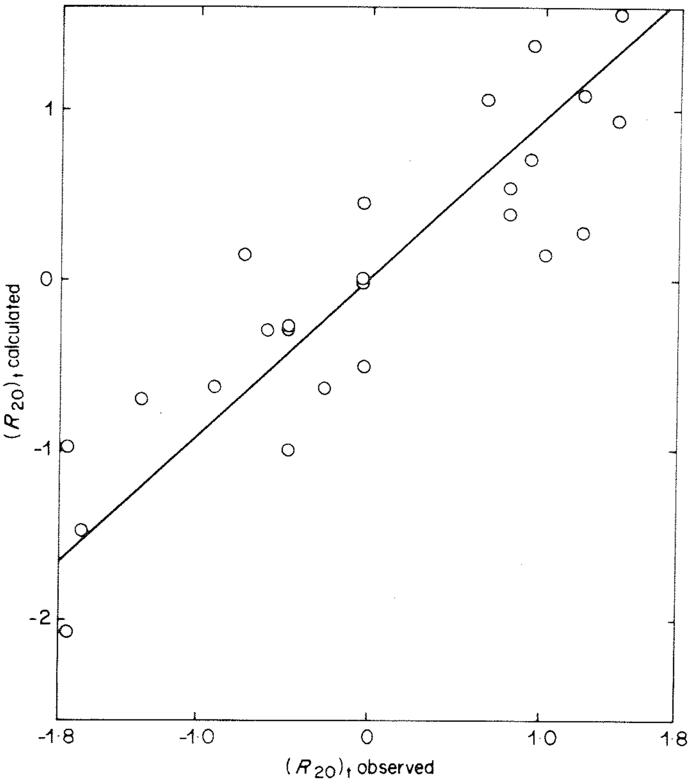

Fig. 8 - Factor analysis applied to the real Maida Vale Studio 1

An attempt to circumvent the above difficulty was made by applying factor analysis using only the eight most significant variables (Section 3.2.2, the variables used in Equation (1)) and extracting the first seven factors (N = 25, n = 8, m = 7). In one sense, this approach was much more successful in that the first factor F1 extracted 55% of the total variance. None of the factors were capable of any obvious psycho-physical interpretation, however, and from this point of view, the exercise was no more successful than the previous one using nineteen variables. Only two of the factors, F1 and F6, correlated well with characteristic No. 20 (overall assessment) and Equation (5) gives a multiple-correlation coefficient of 0·883. Figure 8 shows the

$$R_{20} = -0{\cdot}195F1 + 0{\cdot}590F6 \qquad (5)$$

'goodness of fit' for the 25 observers. Note that the results are here plotted in statistical 't' units, i.e. with zero mean value and unit standard deviation, but this involves only a linear transformation of the original data, i.e. shift of zero and scale change. If it were possible to find names or concepts relating to F1 and F6 it would be possible to claim, substantially, to have 'explained' overall assessment in terms of two factors, at least as far as Maida Vale 1 is concerned.

3.3.3. Ideal Maida Vale Studio 1

No attempt was made to apply factor analysis to these results on account of the relatively small number of questionnaires (N = 14), and the fact that the less sophisticated regression analysis yielded results which were statistically significant but physically meaningless, or, to say the least, difficult to interpret.

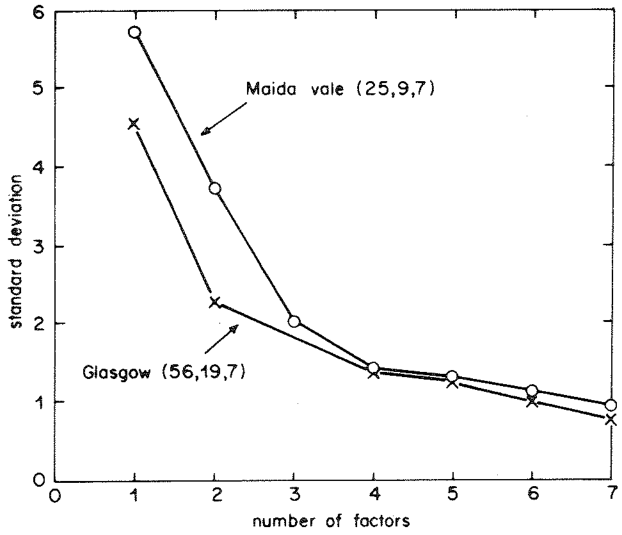

Fig. 9 - Extraction of the factors and their corresponding standard deviations for the real Glasgow Studio 1 and real Maida Vale Studio 1 results. The three numbers in the bracket are numbers of sets of data, number of independent variables and number of factors respectively

3.3.4. Real Glasgow Studio 1

The problem of N exceeding n by a relatively small number does not arise with the Glasgow results where N = 56; n = 19 and m = 7 as before. Hence the probability of relatively high correlations from chance coincidence of sequences of numbers is low. The way in which the variance is extracted by the first seven factors is shown in Figure 9, which also gives the Maida Vale result for comparison. The levels are well above those expected from a truly random set of numbers. Examination of the weightings of the original variables to form the factors once again reveals no obvious psycho-physical significance in that no 'break-points' occur after the first few variables, thus separating them out from the remainder. The first factor, F1, correlates very significantly with the overall assessment (r = −0·57)* and the second is probably significant (r = −0·27).* The remaining five factors do not correlate significantly. Arising out of this factor analysis, Figure 10 shows the measure of agreement between the overall assessment calculated from Equation (6) and the directly observed overall assessment.

$$R_{20} = -0{\cdot}198F1 - 0{\cdot}193F2 \qquad (6)$$

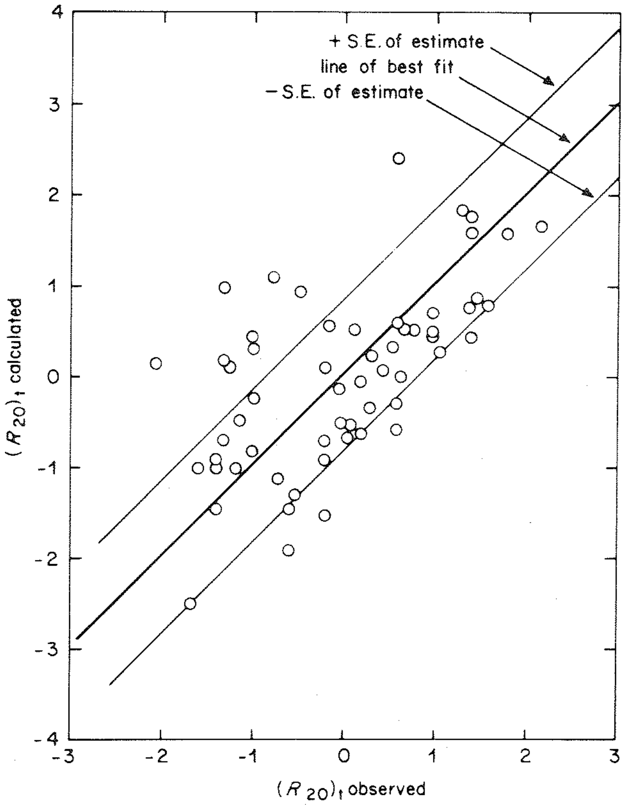

Fig. 10 - Factor analysis applied to the real Glasgow Studio 1

TABLE 6

Order	Factor 1		Factor 2	
	Characteristic	Weighting Coefficient	Characteristic	Weighting Coefficient
1	17 Attack	−0·735	3 Echoes	−0·588
2	5 Singing tone	−0·641	11 Liveness	0·552
3	19 Timbre	−0·633	6 Ensemble	−0·473
4	7 Fullness of tone	−0·608	7 Fullness of tone	0·450
5	18 Dynamic range	−0·607	13 Definition	−0·440

---

* No significance attaches to the negative sign in this context because the polarity of the factors is arbitrary and a new F1 and F2 could easily be defined with opposite signs which would have all the requisite mathematical properties.

The units in Figure 10 are statistical 't' units as in Figure 8. Although a general trend is clearly discernable, the accuracy of estimate is relatively poor, so that Equation (6) cannot be regarded as 'explaining' the way in which judgements were made. The first five characteristics comprising F1 and F2 are listed in Table 6, but it must be acknowledged that the choice of five is entirely arbitrary as there is no 'break-point' between variables 5 and 6.

A comparison of Factor F1 in Table 6 with the corresponding result for Maida Vale 1 (Appendix 2) shows that three of the five characteristics are common, namely singing tone (5), dynamic range (18) and timbre (19). This commonality is possibly significant but too much should not be inferred because, as stated above, there are no logical ground for selecting the first five characteristics.

Factor analysis was not carried out on the questionnaires relating to the Ideal Glasgow Studio, not because there was an inadequate number of questionnaires, but rather because of the almost complete lack of success in the preceeding applications.

4. Conclusions

Various types of analysis have been applied to the raw data and the results have not always yielded significance in the psycho-acoustical sense or in the sense of correlating well with general experience. However, some of the results are probably significant and are certainly interesting.

(a) The considerable similarity in the characteristics of an ideal music studio as given by two dissimilar groups of observers instills confidence that the answers given are a true (or very near to a true) representation of a suitable combination of individual characteristics to define this type of studio.

(b) The real Maida Vale Studio 1 is shown to fall short of the ideal in respect of a considerable number of characteristics. Likewise Glasgow Studio 1 also falls short of the ideal and in many ways the deficiencies appear to be similar to those of Maida Vale 1. Both studios were designed with similar objectives and there is little doubt that the objectives have been largely achieved. This leads one to question whether these objectives are consistent with present-day ideals: perhaps some rethinking of BBC methods of acoustic design is called for. Both studios are of similar volume and it is just possible that they are both not really large enough for a full symphony orchestra. The present analysis is incapable of determining whether this is true or false.

(c) Linear regression analysis applied to the two real studios has produced formulae each of which has a high multiple correlation coefficient. More confidence might be attached to this approach if the formulae had been very similar, but this was not the case in that only four of the eight variables used were common (see Equations (1) and (4)).

(d) The failure to find a few significant factors is disappointing, and poses the query whether the raw data is unsuitable (in the sense that each set of data relates to only one studio), or whether alternative methods of factor analysis should be investigated. In view of the importance of finding answers to the questions, it is felt that further work is required on this problem, which is not capable of an easy solution. One hopeful new approach is offered by the use of a scale model and work using this is now proceeding. A scale model enables changes to be made to a single feature (or a small group of features) and the consequent effects on the acoustics of the hall can then be estimated by subjective assessment techniques coupled with appropriate objective measurements of relevant parameters in the model.

5. References

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5. For example, LAWLEY, D.N. *and* MAXWELL, A.E. 1963. Factor analysis as a statistical method. London, Butterworths, 1963.

APPENDIX 1

Assessment of Acoustic Quality of Maida Vale Studio 1

In order to help us arrive at an agreed assessment of the acoustic qualities of Maida Vale 1 Studio as used for symphonic or choral works, we are asking a selected number of people to fill up the attached questionnaires. You will see that under each heading is a scale running between two extreme descriptions and we would like you to place a cross at a point which indicates your estimate of the extent to which this parameter is possessed by the studio. The cross can be placed anywhere on the scale, not necessarily at the markers.

Example:

Temperature

Warm Cold

. . . . . .

It is important that the forms be returned by August 15th to the following address:

Mr. H.D. Harwood,
BBC Research Department,
Kingswood Warren,
Tadworth,
Surrey.

In order to avoid affecting the investigation we would ask you not to discuss it with anyone else. Do not spend more than five minutes filling up the form.

If you think that there are any important features of Maida Vale 1 Studio which we have not covered would you please mention them in the final remarks column.

To clarify matters we define below a few unusual terms we have used:

Colouration	A characteristic timbre possibly having a locateable pitch.
Diffusion	A sense that the reverberant sound comes from all directions at once.
Dynamic Range	The difference in loudness between the quietest and loudest sound in the studio.

In addition to help us assess the meaning of your judgement we would ask you to fill in Form 2 indicating your idea of an ideal studio.

FORM 1A

1. Colouration
0 Highly Coloured
10 Not Coloured

2. Diffusion
0 Poorly Diffused
10 Well Diffused

3. Echoes
0 Prominent Echoes
10 No Echoes

4. Pitch Changes
10 No Pitch Changes
0 Large Pitch Changes

5. Singing Tone
10 Good Singing Tone
0 Poor Singing Tone

6. Ensemble
0 Poor Ensemble
10 Good Ensemble

7. Fullness of Tone
10 Full Tone
0 Thin Tone

8. Hardness
0 Hard
10 Mellow

9. Loudness
0 Quiet
10 Loud

10. Intimacy
10 Intimate
0 Distant

11. Liveness
0 Dead
10 Live

12. Tonal Warmth
10 Warm
0 Cold

FORM 1A
CONTINUED

13. **Definition**
0 Muddy — 10 Clear

14. **Brilliance**
10 Brilliant — 0 Dull

15. **Balance**
0 Unbalanced — 10 Balanced

16. **Blend**
10 Well Blended — 0 Not Blended

17. **Attack**
0 Poor Attack — 10 Good Attack

18. **Dynamic Range**
10 Large — 0 Small

19. **Timbre**
0 Poor — 10 Good

20. **Overall**
10 Liked — 0 Disliked

21. **Remarks:**

Signature . . . . Date . . . .

APPENDIX 2

Maida Vale 1 Factor Analysis

Factor F1 is highly correlated with R_{20} (r = 0·809); it contains all 19 variables (as do factors F2 to F7), but range of weighting coefficients vary from 0·8279 (No. 5) to 0·0446 (No. 3).

Complete list is as follows:

Order	Coefficient	Quality	Description
1	·8279	5	Singing tone
2	·7851	6	Ensemble
3	·7637	18	Dynamic range
4	·7631	13	Definition
5	·7051	19	Timbre
6	·6756	17	Attack
7	·6585	7	Fullness of tone
8	·6061	15	Balance
9	·5947	12	Tonal warmth
10	·5940	16	Blend
11	·5013	14	Brilliance
12	—·4555	9	Loudness
13	·3695	8	Hardness
14	·3600	11	Liveness
15	·2082	10	Intimacy
16	·0678	1	Colouration
17	·0654	2	Diffusion
18	·0468	4	Pitch changes
19	·0446	3	Echoes

Factor F2 is much less well correlated with R_{20} (r = 0·260); it contains all 19 variables with weighting factors ranging from 0·7993 to 0·0305.

Complete list:

Order	Coefficient	Quality	Description
1	·7993	1	Colouration
2	—·7514	11	Liveness
3	—·6609	9	Loudness
4	—·6075	2	Diffusion
5	—·5213	8	Hardness
6	—·5011	12	Tonal warmth
7	—·4862	7	Fullness of tone
8	—·4511	4	Pitch changes
9	·4378	10	Intimacy
10	·4190	13	Definition
11	—·3075	17	Attack
12	·2925	18	Dynamic range
13	·2713	6	Ensemble
14	·2173	14	Brilliance
15	—·1905	3	Echoes
16	·1747	15	Balance
17	—·1559	5	Singing tone
18	·0822	16	Blend
19	·0305	19	Timbre

Factor F3 has correlation coefficient of 0·0581 with R_{20}; No. 4 (Pitch Changes) is highest on the list with a coefficient of —0·6841; No. 6 (Ensemble) is lowest.

Complete list as follows:

Order	Coefficient	Quality	Description
1	—·6841	4	Pitch changes
2	·6282	8	Hardness
3	—·4856	14	Brilliance
4	·3754	12	Tonal warmth
5	·3404	7	Fullness of tone
6	—·3338	17	Attack
7	—·3203	2	Diffusion
8	—·3120	10	Intimacy
9	—·2990	11	Liveness
10	—·2816	9	Loudness
11	—·2139	13	Definition
12	—·1711	15	Balance
13	—·1694	16	Blend
14	·1448	5	Singing tone
15	·1336	19	Timbre
16	·1124	18	Dynamic range
17	·0875	3	Echoes
18	·0766	1	Colouration
19	—·0698	6	Ensemble

Factor F4 correlates with R_{20} with coefficient 0·0400; Echoes (No. 3) is the predominant characteristic; seven of the characteristics have coefficients less than 1/10 that of 'Echoes'.

Order	Coefficient	Quality	Description
1	—·8251	3	Echoes
2	·4501	15	Balance
3	—·3975	14	Brilliance
4	·2615	19	Timbre
5	·2492	2	Diffusion
6	—·2428	17	Attack
7	·2337	4	Pitch changes
8	—·1858	6	Ensemble
9	·1720	1	Colouration
10	·1302	5	Singing tone
11	·1247	16	Blend
12	—·1188	13	Definition
13	·0709	7	Fullness of tone
14	·0689	10	Intimacy
15	·0473	18	Dynamic range
16	—·0310	8	Hardness
17	·0255	11	Liveness
18	—·0207	9	Loudness
19	·0043	12	Tonal warmth

Factor F5 correlates with R_{20} with a coefficient of 0·0169; Intimacy (No. 10) appears to the one predominant characteristic; r = ·0169, highest coefficient = ·6361, lowest coefficient = ·0220.

Order	Coefficient	Quality	Description
1	—·6361	10	Intimacy
2	·3767	19	Timbre
3	—·3158	4	Pitch changes
4	·3110	15	Balance
5	·2896	2	Diffusion
6	—·2807	7	Fullness of tone
7	—·2320	12	Tonal warmth
8	·2265	13	Definition
9	·2250	9	Loudness
10	—·2214	17	Attack
11	·1916	14	Brilliance
12	·1795	18	Dynamic range
13	—·1743	5	Singing tone
14	·1302	3	Echoes
15	—·0890	6	Ensemble
16	·0664	11	Liveness
17	·0449	16	Blend
18	—·0445	1	Colouration
19	·0220	8	Hardness

Factor F6 correlates with R_{20} with a coefficient of —0·1536; there is no outstanding characteristic and the weighting coefficients vary from —0·4516 to —0·0171.

Order	Coefficient	Quality	Description
1	—·4516	2	Diffusion
2	·3582	14	Brilliance
3	—·3555	10	Intimacy
4	—·3477	18	Dynamic range
5	—·3344	3	Echoes
6	—·2571	8	Hardness
7	—·1840	16	Blend
8	·1758	12	Tonal warmth
9	·1657	13	Definition
10	—·1528	6	Ensemble
11	—·1474	1	Colouration
12	·1309	5	Singing tone
13	·1261	7	Fullness of tone
14	·1082	19	Timbre
15	—·0814	15	Balance
16	—·0741	9	Loudness
17	·0647	11	Liveness
18	·0489	17	Attack
19	—·0171	4	Pitch changes

Factor F7 correlates with R_{20} with a coefficient of —0·1066. 13 qualities are included before any 'break point' appears. Highest coefficient = ·4072, lowest coefficient = ·0129.

Order	Coefficient	Quality	Description
1	—·4072	19	Timbre
2	·3637	1	Colouration
3	—·3304	6	Ensemble
4	·2625	2	Diffusion
5	·2293	7	Fullness of tone
6	·1985	12	Tonal warmth
7	·1850	13	Definition
8	—·1772	4	Pitch changes
9	·1530	15	Balance
10	—·1527	18	Dynamic range
11	·1500	16	Blend
12	·1468	14	Brilliance
13	—·1450	5	Singing tone
14	—·0729	9	Loudness
15	·0514	17	Attack
16	·0431	11	Liveness
17	—·0348	10	Intimacy
18	·0225	8	Hardness
19	—·0129	3	Echoes

APPENDIX 3

Relevance of Weighting Coefficients

It is not necessarily true that weighting coefficients in a linear regression equation describing acoustic quality are related to deficiencies in the acoustics of a studio. In fact, as a general statement it is probably untrue. In the present investigation, however, the situation is that fifteen of the twenty-five observers gave adverse judgements of Maida Vale 1 (i.e. overall rating on a like/dislike axis of less than 5) and it is probable that those qualities which correlate highly with the overall rating are also those which caused the unfavourable judgements. Hence these are the qualities the ratings of which, in the view of more than half the observers, ought to be changed so that the acoustics of Maida Vale 1 should be improved. This is clearly not an argument that can be strictly proven on logical grounds and the whole approach of using correlation analysis on only one studio makes assumptions which are doubtful, to say the least. However, the apparent success of the exercise (in the sense of producing multiple correlation coefficient of about 0·9) tends to strengthen the view that this approach may well give some useful and significant information.

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